

# Single crystal growth and physical properties of $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$

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We report a crystal growth and physical properties of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$ . The single crystals for various  $x$ s were grown by a self flux method. For  $x = 0.35$ ,  $T_c$  reaches the maximum value of 30 K and the electrical resistivity  $\rho(T)$  shows  $T$ -linear dependence. As  $x$  increases,  $T_c$  decreases and  $\rho(T)$  changes to  $T^2$ -behavior, indicating a standard Fermi liquid. These results suggest that a magnetic quantum critical point exists around  $x = 0.35$ .

**KEYWORDS:** Ternary  $\text{ThCr}_2\text{Si}_2$  type iron-pnictide, superconductors, synthesis of single crystal.

## 1. INTRODUCTION

Iron pnictide superconductor  $\text{LaFeAsO}_{1-x}\text{F}_x$  was discovered in 2008, which shows  $T_c = 26 \text{ K}$ <sup>1)</sup>. Soon after the discovery,  $\text{RFeAsO}_{1-x}\text{F}_x$  ( $R = \text{Ce, Pr, Sm, Nd}$ ) was found and the maximum  $T_c$  reached 55 K. Moreover, new iron pnictide or chalcogenide superconductors with different crystal structure such as  $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ,  $\text{LiFeAs}$ ,  $\text{FeSe}_{1-x}$  and  $\text{KFe}_2\text{Se}_2$  were reported one after another, but the superconducting mechanism is still unclear despite many intensive researches.

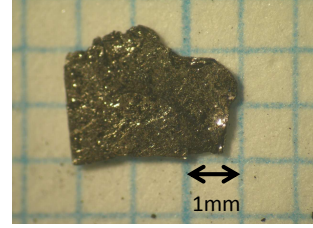
Superconductivity in  $\text{AFe}_2\text{As}_2$  ( $A = \text{Ba, Sr, Ca, Eu}$ , so called A122 system) is induced by hole-doping (K substitution for A) and electron-doping (Co for Fe). Additionally, isovalent substitution (P for As) also induces superconductivity. This system, particularly  $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ , attracts attention in terms of magnetic quantum criticality and the nodal superconducting gap feature<sup>2)</sup> in contrast to a full gap for most of the other iron based superconductors<sup>3,4)</sup>. Compared with many investigation for  $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ , the study of the related system,  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  is never reported except the polycrystal study<sup>5)</sup>, thus the study with single crystals is needed to elucidate the superconducting mechanism of P substituted A122 system.

In this study, we synthesized single crystals of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  and measured the physical properties to clarify a phase diagram and anomalous resistivity behaviors in the vicinity of magnetic quantum critical point.

## 2. EXPERIMENTAL

$\text{AFe}_2\text{As}_2$  can be synthesized by several flux methods. In this study,  $\text{SrFe}_2\text{As}_2$  was synthesized with Sn flux method. Sr chunks, FeAs and Sn were loaded in an alumina crucible according to the ratio of  $\text{Sr}+2\text{FeAs}:\text{Sn} = 1:25\text{-}40$ . The alumina crucible in a sealed silica tube was heated up to  $1020^\circ\text{C}$ , kept for 12 hours, and then cooled down to  $600^\circ\text{C}$  over 122 hours. Sn flux was removed by using centrifuge. Plate like single crystals with typical size of  $4 \times 4 \times 0.5 \text{ mm}^3$  were obtained.

On the other hand,  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  could not be obtained by a Sn flux or a self flux method using excess FeAs. So we grew single crystals of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  from stoichiometric mixtures of Sr, FeAs, and FeP powders placed in an alumina crucible, sealed in a silica tube with Ar gas of 0.2 bar at room temperature to prevent Sr from evaporating. It was heated up to 1230-1300 °C relatively higher temperature than the case of crystal growth of Co substituted systems, kept for 12 hours, and then slowly cooled down to 1050 °C at the rate of 1-2 °C/h. Plate-like crystals, typical size of  $1 \times 1 \times 0.13 \text{ mm}^3$  were extracted (Fig. 1). The crystal size tends to become smaller as  $x$  increases.

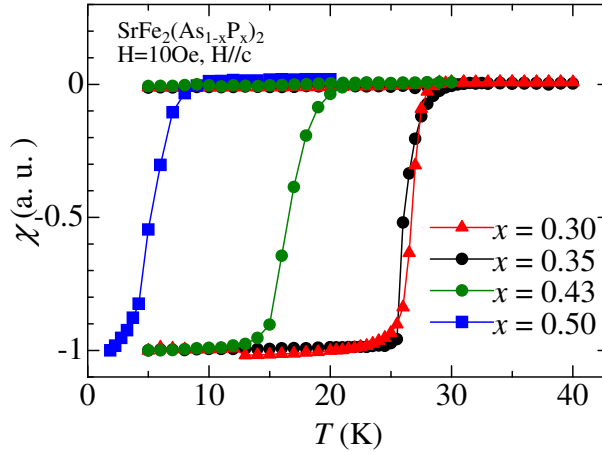


**Fig. 1.** (Color online) Photograph of single crystal of  $\text{SrFe}_2(\text{As}_{0.65}\text{P}_{0.35})_2$ .

The electrical resistivity was measured by a standard four-probe method and the magnetic susceptibility was measured by a magnetic property measurement system (MPMS) of Quantum Design Company.

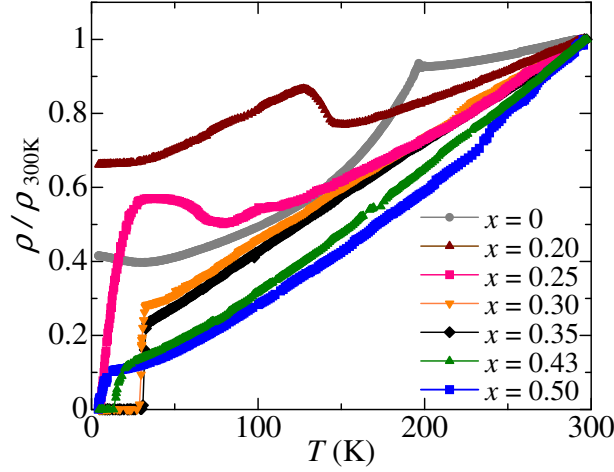
### 3. RESULT AND DISCUSSION

Figure 2 presents the temperature dependent magnetic susceptibility in 10 Oe, normalized to their lowest zero-field-cooled values. In zero-field-cooled data, there is a clear drop at the temperature associated with superconductivity. The field-cooled susceptibility data manifest clear Meissner effect.

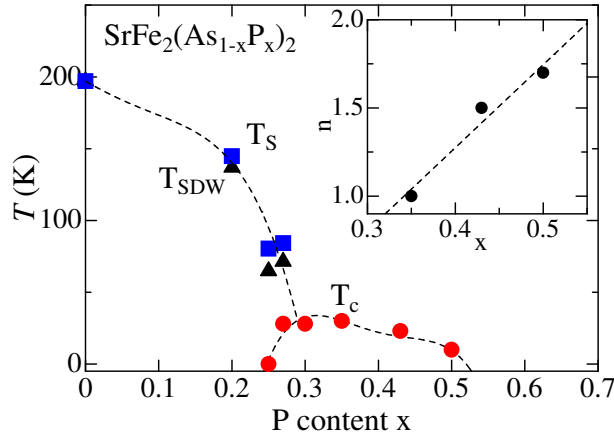


**Fig. 2.** (Color online) Temperature dependence of magnetic susceptibility  $\chi$  of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  in magnetic field of  $x = 0.30, 0.35, 0.43, 0.50$ . Measurements were performed the field-cooled and zero-field-cooled process at 10 Oe with  $H \parallel c$ .

Figure 3 shows the temperature dependent in-plane electrical resistivity of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  series, normalized to their room temperature value. For  $\text{SrFe}_2\text{As}_2$ , a sharp drop in resistivity at 197 K is related to the structural and SDW transition. The upturn around 30 K is due to the contamination of Sn. With P content increasing, the resistivity anomaly is suppressed and zero resistivity is attained at  $x = 0.25$ , indicating the coexistence of SDW and superconductivity. A superconducting temperature  $T_c$  rises to 30 K at  $x = 0.35$ . With more P substitution,  $T_c$  is lowered to 20 K at  $x = 0.43$  and 10 K at  $x = 0.50$ . For  $x = 0.35$ , the resistivity exhibits  $T$ -linear dependence in a wide  $T$  range which suggests that a non Fermi liquid like behavior governed by a magnetic quantum fluctuation. As  $x$  further increases, the temperature dependence of resistivity changes towards  $T^2$  which is consistent with a standard Fermi liquid behavior.



**Fig. 3.** (Color online) Temperature dependence of the in-plane electrical resistivity of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  for  $x = 0, 0.20, 0.25, 0.30, 0.35, 0.43, 0.50$ , normalized to the room temperature value.



**Fig. 4.** (Color online)  $T$ - $x$  phase diagram of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  single crystals for  $0 \leq x \leq 0.50$ .  $T_s$ ,  $T_{\text{SDW}}$  and  $T_c$  are determined from the resistivity and susceptibility measurements. The inset represents the power  $n$  in resistivity fitted by  $\rho(T) = \rho_0 + AT^n$ .

Figure 4 displays the temperature-doping concentration ( $T$ - $x$ ) phase diagram obtained in this study. Structural, SDW and superconducting transition temperature were inferred from the resistivity and magnetic susceptibility measurements. Square symbols represent the structural transition temperature,  $T_s$ , while triangle symbols represent the magnetic transition temperature,  $T_{\text{SDW}}$ . As it can be seen, the phase transition temperatures monotonically decrease as P content increases. For  $x > 0.25$ , a dome like superconducting phase appears, while the structural / magnetic transition disappears. The superconducting transition temperature,  $T_c$ , which is represented by circle symbols, reaches maximum value of 30 K for  $x = 0.30$  and  $0.35$ , then decreases to 20 K at  $x = 0.43$  and 10 K at  $x = 0.50$ . The inset represents the exponent  $n$  in resistivity fitted by  $\rho(T) = \rho_0 + AT^n$ . The  $n$  changes from 1 of the non Fermi liquid toward 2 of the Fermi liquid with increasing  $x$ . This change suggests that the antiferromagnetic quantum critical point exists around  $x = 0.35$ . In addition, the recent NMR measurement of our single crystal of  $\text{SrFe}_2(\text{As}_{0.65}\text{P}_{0.35})_2$  also found that it was close to the magnetic quantum critical point<sup>(6)</sup>.

## 4. SUMMARY

We have synthesized the series of single crystals of  $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$  and studied the physical properties. The result of resistivity measurement revealed the pronounced non-Fermi-liquid like behavior at the SDW quantum critical point around  $x = 0.35$ . This behavior is similar result of P substituted Ba122, suggesting that antiferromagnetic fluctuation plays an important role in the superconducting mechanism in this P substituted 122 system.

## 5. ACKNOWLEDGEMENT

This research was supported by Strategic International Collaborative Research Program (SICORP), Japan Science and Technology Agency.

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